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Fifty-year climate change and its effect on annual runoff in the Tarim River Basin, China

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ABSTRACT

Based on the hydrologic and meteorological data in the Tarim River basin from 1958 to 2004, the trend, characteristics and spatial variation of climate change in the upper reaches of the Tarim River were examined in the study. The long-term trend of climate change and hydrological variations were determined by using both Mann–Kendall and Mann–Whitney nonparametric tests. The results showed that the temperature and precipitation had significantly increased in the drainage basin in the mid-1980s. The climate was the warmest in 1990s among the recent 50 years. The increase of temperature in the tributaries of the Aksu River and Kaidu-Kongque River is higher than that in the tributaries of the Yarkand River and Hotan River. The streamflow at Aksu River showed a significant increasing monotonic trend. The annual runoff in the Aksu River had increased by 10.9% since 1990. The independence test of temperature and precipitation with χ^2 of the El Nino event reveals that there is no significant effect of the El Nino and La Nina events on the annual temperature and annual precipitation in the drainage basin.

1. Introduction

Climatic system is a highly complicated system composed of atmosphere, hydrosphere, cryosphere, geosphere and biosphere (Qin et al., 2005). Climate change affects not only the environment on which human beings rely for existence, but also the various aspects of social and economic development. Climate change caused by human activities has been recognized by scientific community (IPCC, 1996; IPCC, 2001; Kamga, 2001), and it is becoming a critical international problem affecting global development in this century. The global temperature has risen by 0.3–0.4 °C in recent 100 years and by 0.2–0.3 °C in recent 35 years (IPCC, 1996). The annual temperature in China had risen by 0.3 °C during the period from 1951 to 1990 (Ding, 2002). Some evidence also showed that the climate change in Xinjiang is significant in recent 50 years, especially in the last 20 years (Chen and Xu, 2005).

The Tarim River Basin is located in south Xinjiang and covers about two thirds of the total area of Xinjiang. The climate change in Xinjiang clearly has significant impact on the climate in the Tarim River Basin. Climate change in the Tarim River Basin is coinstantaneous with that in whole Xinjiang and global climate change to a certain extent, but also has its own patterns. Therefore it is conductive to understand the change and response of hydrological process by examining the long-term trend, characteristics and spatial variation of climate change in a drainage basin.

2. Materials and methods

2.1. Study area

Located in an arid area in Northwest China, the Tarim River is the largest inland river in China. The Tarim River Basin is composed of 114 rivers in 9 stream systems surrounding the Tarim Basin, with a catchment area of 1.02×10^6 km^2. Tarim River is mainly recharged by alpine glacier-snow melt water and rainfall and has 3.98 × 1010 m^3 of average surface runoff in the long-term. The Tarim River basin is a closed catchment area, but also has a unique freshwater ecosystem close to the Taklimakan Desert, the largest desert in China.

The mainstream of the Tarim River is 1321 km. In the history, there had been nine water systems flowing into the mainstream of Tarim River. With the intensive disturbance of human activities, especially the exploitation of water resources, great changes have taken place in recent 50 years, the water systems gradually dismembered, only three water systems have the natural hydraulic relationship with the mainstream. They are Aksu river, originating

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from the Tianshan Mountains is located in the northwestern part of the basin, the Hotan river, from Kunlun Mountains, is in the southwestern part of the basin, and the Yarkand river is located between the Hotan and Aksu rivers (Fig. 1). Among the three main headstreams, the proportions of water recharge from the Aksu River, the Hotan River and the Yarkand River account for 73.2%, 23.2% and 3.6%, respectively (Chen et al., 2003). Kaidu River transports water to the irrigation area of the lower reaches of the Tarim River from Bosten Lake sometimes. These four rivers play an important role in economic development and ecological conservation in the Tarim River Basin.

The Tarim River Basin has an extreme drought desert climate with an average annual temperature of 10.6–11.5 °C and precipitation of 17.4–42.0 mm. Monthly mean temperature ranges from 20 °C to 30 °C in July and −10 °C to −20 °C in January. The highest and the lowest temperature are 43.6 °C and −27.5 °C respectively. The accumulated temperature above 10° ranges from 4100 to 4300 °C. The average annual precipitation ranges from 200 to 500 mm in the mountainous area, 50–80 mm on the side of the basin, and only 10 mm in the central basin, and 116.8 mm in the study area. The precipitation throughout the year is unevenly distributed. More than 80% of total annual precipitation occurs between May and October and less than 20% between November and April.

2.2. Data collections

The temperature, precipitation and runoff monthly data for 1957–2004 in this study were collected from six hydrological stations in the headstreams of the Tarim river (Fig. 1). The Tongguzlok and Uruwat stations are located over the Hotan River, Kaqung station over the Yarkand River, Shrikilank and Xehera stations over the Aksu River, and Dashankou station over the Kaidu River. All stations are located at the mountains where anthropogenic disturbance is negligible. Table 1 shows the information about the hydrological stations and the hydrological eigen values in the Tarim River Basin.

The hypothesis testing for the long trend of climate change is helpful to understand the inherent mechanism of hydrological process. Generally two types of trends are considered: one is the monotonic trend; the other is the step (shift) change (Hirsch et al., 1991). In the trends test, the null hypothesis H_0 is that there is no trend in population from which the data set X is drawn. While the alternative hypothesis H_1 is that there is obvious trend in the record. It is known that both parametric and nonparametric tests can be used for trend detection. However, the power of the test, i.e. the ability to distinguish between H_0 and H_1, the Mann–Whitney test for step changes and the Mann–Kendall test for monotonic trends perform well in comparison to the parametric t-test (Belle and Hughes, 1984). Therefore, the nonparametric test was employed to detect the long trend for climate change (Xu et al., 2003).

2.2.1. Mann–Kendall test for monotonic trend

In this study, the nonparametric Mann–Kendall method is used to detect possible trends in hydrological processes. In which, the test statistic is given as follows:

$$Z_c = \begin{cases} \frac{S-1}{\sqrt{\mathrm{var}(S)}}, & S>0 \\ 0, & S=0 \\ \frac{S+1}{\sqrt{\mathrm{var}(S)}}, & S<0 \end{cases} \tag{1}$$

where

$$S = \sum_{i=1}^{n-1} \sum_{k=i+1}^{n} \mathrm{sgn}(x_k - x_i) \tag{2}$$

$$\mathrm{sgn}(\theta) = \begin{cases} 1, & \theta>0 \\ 0, & \theta=0 \\ -1, & \theta<0 \end{cases} \tag{3}$$

$$\mathrm{var}[S] = \left[n(n-1)\,(2n+5) - \sum_t t(t-1)\,(2t+5)\right] \Big/ 18 \tag{4}$$

in which the x_k, x_i are the sequential data values, n is the length of the data set, t is the extent of any given tie, and Σ denotes the summation over all ties.

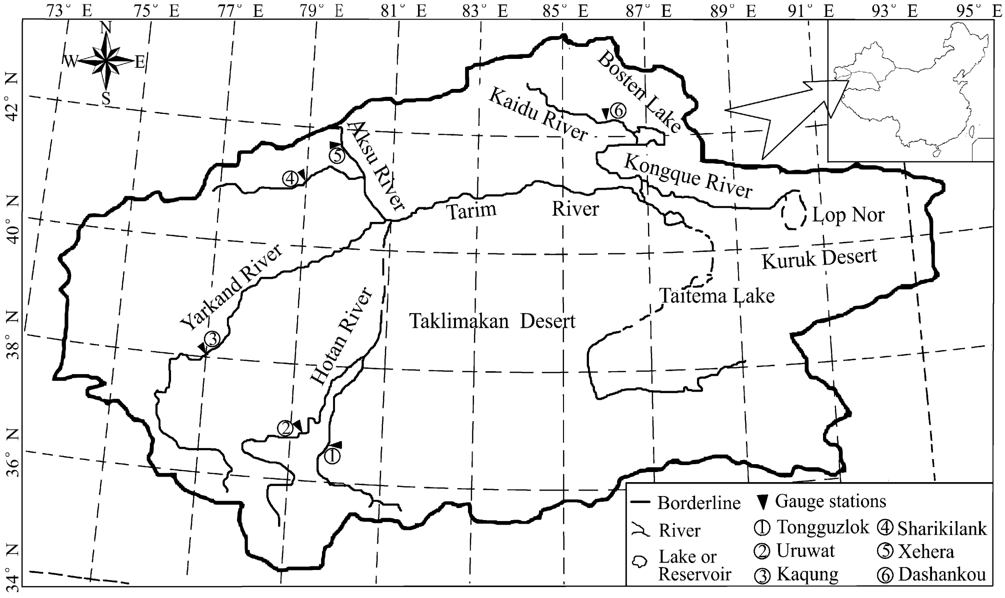

Fig. 1. Sketch map of the Tarim River basin.

Table 1
Information about the hydrological stations and the hydrological eigen values in the Tarim River Basin.

River name		Hydrological station	Catchment area (km^2)	Annual runoff volume (10^8 m^3)	Runoff composition (%)		
					Glacier melt water	Snow melt water and rainfall	Base flow
Aksu River	Toxkan River	Sharikilank	19166	27.67	24.7	45.1	30.2
	Kunmarik River	Xehera	12816	48.67	52.4	30.4	17.2
Yarkand River	Yarkand River	Kaqung	50248	65.43	64	13.4	22.6
Hotan River	Yurungkax River	Tongguzlok	14575	22.27	64.9	17	18.1
	Karakax River	Uruwat	19983	21.39	54.1	22.1	23.8
Kaidu-kongque River	Kaidu River	Dashankou	18827	34.2	14.1	45.3	40.6

The magnitude of the trend is given as

$$\beta = \text{Median}\left(\frac{x_i - x_j}{i - j}\right), \quad \forall j < i \tag{5}$$

in which $1 < j < i < n$. A positive value of β indicates an 'upward trend', and a negative value of β indicates a 'downward trend'. The Mann–Kendall test is given as follows,

The Mann–Kendall test may be thereby stated simply as follows
Null hypothesis H_0:$\beta = 0$, (β is the slope of trend)
Significance level: α
Test statistics: Z_c
Rejected $H_0 : |Z_c| > Z_{1-\alpha/2}$, in which $\pm Z_{1-\alpha/2}$ are the standard normal deviates, and α is the significance level for the test.

2.2.2. Mann–Whitney test for step trend

Given the data vector $X = (x_1, x_2, \ldots, x_n)$, partition X such that $Y = (x_1, x_2, \ldots, x_{n1})$ and $Z = (x_{n1+1}, x_{n1+2}, \ldots, x_{n1+n2})$. The Mann–Whitney test statistic is given as

$$Z_c = \frac{\sum_{t=1}^{n_1} r(x_t) - n_1(n_1 + n_2 + 1)/2}{[n_1 n_2 (n_1 + n_2 + 1)/12]^{1/2}} \tag{6}$$

in which $r(x_t)$ is the rank of the observations. The null hypothesis H_0 is accepted if $-Z_{1-\alpha/2} \le Z_c \le Z_{1-\alpha/2}$, where $\pm Z_{1-\alpha/2}$ are the $1 - \alpha/2$ quantiles of the stand normal distribution corresponding to the given significance level α for the test.

3. Results and discussion

3.1. Nonparametric test of the temporal series of air temperature

Air temperature is one of the important factors used to evaluate climate change. Fig. 2 shows the temporal series of temperature in the Tarim River Basin from 1958 to 2004. The figure reveals that the temperature in the drainage basin has been significantly increased since the lowest temperature in 1978, and the temperature fluctuated in the decade of the 1970s. The Mann–Whitney phasic-change test with significance level 5% reveals that there must be a significant mean difference in the sub-series of the temporal series. Therefore, it can be considered that there is a significant phasic increase in the series (Hirsch et al., 1991). Mean difference maximization is the basis for judgment. It was found the mean difference between the two sub-series divided by year 1985 is the largest with 0.7 °C (Table 2). It can be also clearly noted from Fig. 2 that 1986 was a cut-off point when a significant step change appeared. The original assumption is rejected by the Mann–Whitney test. Thus, we can conclude that a significant phasic temperature increase has occurred from the abrupt point in 1986. The results of Mann–Kendall monotonic trend test reveal that the original assumption is accepted for the sub-series during the period from 1958 to 1986 but rejected for the sub-series during the period from 1987 to 2004 (Table 2). The results suggest that there was no significant temperature decrease from 1958 to 1986, but a significant temperature increase from 1987 to 2004. The annual temperature in 1990 was higher than 10 °C compared with the average temperature during the period from 1958 to 1989. The 1990s was the warmest decade in past 50 years (Fig. 2). Temperature increase in the Tarim River Basin should be an active local response to global warming and global climate change.

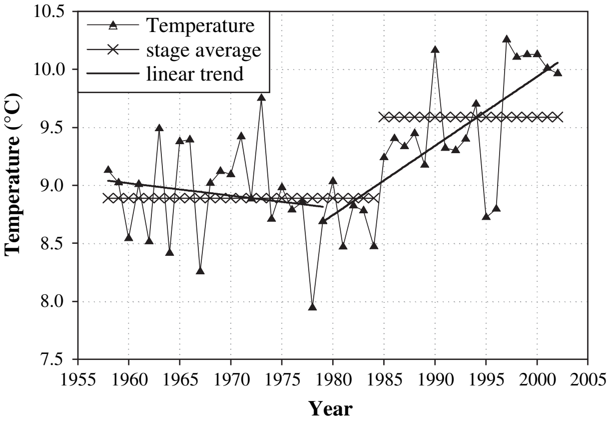

Fig. 2. Average annual temperature in the Tarim River Basin and its linear trend.

In order to investigate the main seasons of temperature increase in the Tarim River Basin, we used seasonal sub-series, i.e. spring (from March to May), summer (from June to August), autumn (from September to November) and winter (from December to next February). The arithmetic mean of seasonal temperature at all the stations is regarded as the integrated temperature series in the drainage basin to carry out the monotonic trend test. Our results revealed that the original assumption was rejected by the seasonal temperature in autumn and winter but accepted by that in spring and summer (Table 2), suggesting significant temperature increase in autumn and winter but not in spring and summer.

The curve fitting analysis revealed that the trend slope coefficient of air temperature in winter (0.04) is higher than that in autumn (0.03), suggesting that temperature increase in winter was higher than that in autumn. The multi-year average temperature in winter in the 1960s was −7.44 °C. It was slightly decreased to −7.88 °C in the 1970s but increased to −6.57 °C in the 1980s and −5.95 °C in the 1990s. On average, it is currently increased by 0.37 °C/decade. Climate warming results in the fatal effects to the natural ecosystems. One of the obvious effects is to change the hydrological cycle and runoff variability in drainage basin and affect various aspects of human life (Xu, 2000).

3.2. Nonparametric test of the temporal series of precipitation

The Mann–Whitney phasic-change test of precipitation series revealed that the mean difference between the two sub-series during the periods of 1958–1986 and 1987–2004 was the highest, and the significance level was at 5% (Table 3), therefore there might

Table 2
Partitions and test results of the temperature time series.

		Time series	Average (°C)	Sd. (°C)	Cv.	Mann–Whitney		Mann–Kendall		Slope of the trend line	p
						Z_{c1}	H_0	Z_{c2}	H_0		
Temperature	1	1958–2004	9.17	0.55	0.06	−4.05	R	3.56	R	0.02	0.000
	2	1958–1984	8.89	0.41	0.05			−1.75	A		
	3	1985–2004	9.59	0.48	0.05			2.04	R	0.05	0.032
	1	Spring (3–5)	11.43	0.76	0.07			0.31	A		
	2	Summer (6–8)	21.76	0.61	0.03			1.49	A		
	3	Autumn (9–11)	9.14	0.77	0.08			3.97	R	0.03	0.001
	4	Winter (12–2)	−6.95	1.47	0.21			3.09	R	0.04	0.012

Note: R – rejected, A – accepted, *P* – Significant level.

be a significant phasic increase in the precipitation series. Moreover, Fig. 3 showed that the series before the mid-1980s was dominated by negative anomaly but by positive anomaly after that, and an abrupt increase of precipitation occurred in 1987. The Mann–Kendall monotonic trend test of precipitation series revealed that the trend of precipitation increase during the period from 1958 to 1986 was not significant, but was significant during the period from 1987 to 2004, suggesting that the precipitation has been increased since the mid-1980s. Such results were consistent with other findings (Shi et al., 2002; Li et al., 2003). Although the climate in the Tarim River Basin changes from the warming–drying trend to the warming–wetting trend, the arid climatic environment in the drainage basin cannot be qualitatively changed by a short-term precipitation increase due to the peculiar geographical location and the climatic conditions (Table 3). The climate change trend in the drainage basin needs to be further validated using longer temporal series.

In order to investigate the seasonal change of precipitation in the Tarim River Basin, the data of precipitation during the period from 1958 to 2004 are further analyzed. The Mann–Kendall analysis results revealed that the precipitation increase was not so significant in spring, autumn and winter but significant in summer (Table 3). Therefore, the precipitation increase occurred mainly in summer.

3.3. *Spatiotemporal change of temperature and precipitation*

The headstream area of the Tarim River Basin is divided into 4 climatic subareas, i.e. the Kaidu-Kongque River subarea (A), Aksu River subarea (B), Yarkand River subarea (C) and Hotan River subarea (D), and the information about the typical stations in these 4 subareas is shown as Table 4.

3.3.1. *The Kaidu-Kongque River subarea*

In the Kaidu-Kongque River subarea, the annual temperature was dominated by a negative anomaly during the period from the 1960s to the 1980s, an abrupt change of annual temperature occurred in the 1990s, the annual temperature in the 1990s was increased by 0.6 °C comparing with the average during the period from 1971 to 2003, and a significant local warming occurred (Fig. 4a).

Some patterns of annual distribution are as follows: (1) In spring the temperature decreased in the 1980s, significantly contributing to the low temperature in the Kaidu-Kongque River subarea in the 1980s. The temperature in spring in the 1990s increased by 0.39 °C comparing with the multi-year average. (2) In summer, the temperature increased all along (the highest in the 1990s), but increased by 0.26 °C only, the lowest among the four seasons. (3) In autumn, the temperature increase was similar to that in summer, but became higher in the 1990s; the temperature increased by 0.67 °C comparing with the multi-year average. (4) In winter the temperature in the 1970s was 0.74 °C lower than the multi-year average. However, it began to increase from the 1980s. The temperature in winter in the 1990s increased by 0.88 °C comparing with the multi-year average. Temperature in the Kaidu-Kongque River subarea in the 1990s increased rapidly, especially in winter and then in autumn. Generally, the seasonal temperature in the Kaidu-Kongque River subarea was dominated by negative anomaly during the period from the 1960s to the 1980s but by positive anomaly in the 1990s.

Annual precipitation in the subarea was dominated by slight negative anomaly during the period from the 1960s to the 1980s with an abrupt precipitation increase occurred in the 1990s; then the precipitation anomaly became positive, and the anomaly percentage was as high as 13.2%, in which the contribution of precipitation in summer and winter to the precipitation increase was high, followed by spring, but the precipitation in autumn was significantly decreased. Viewing from the whole drainage basin, both temperature and precipitation have been coinstantaneously increased since the 1990s.

3.3.2. *The Aksu River subarea*

In the Aksu River subarea, the annual temperature in the 1970s decreased to a certain extent, in which the contributions of

Table 3
Partitions and test results of the precipitation time series.

		Time series	Average (mm)	Sd. (mm)	Cv.	Mann–Whitney		Mann–Kendall		Slope of the trend	p
						Z_{c1}	H_0	Z_{c2}	H_0		
Precipitation	1	1958–2004	112.81	26.39	0.23	−3.44	R	2.69	R	0.72	0.016
	2	1958–1986	102.76	22.84	0.22			−0.99	A		
	3	1987–2004	131.02	22.84	0.17			1.98	R		
	1	Spring (3–5)	29.81	9.55	0.32			−0.01	A		
	2	Summer (6–8)	60.15	19.44	0.32			2.67	R	0.56	0.010
	3	Autumn (9–11)	17.52	9.30	0.53			1.87	A		
	4	Winter (12–2)	7.90	4.16	0.53			0.98	A		

Note: R – rejected, A – accepted, *P* – Significant level.

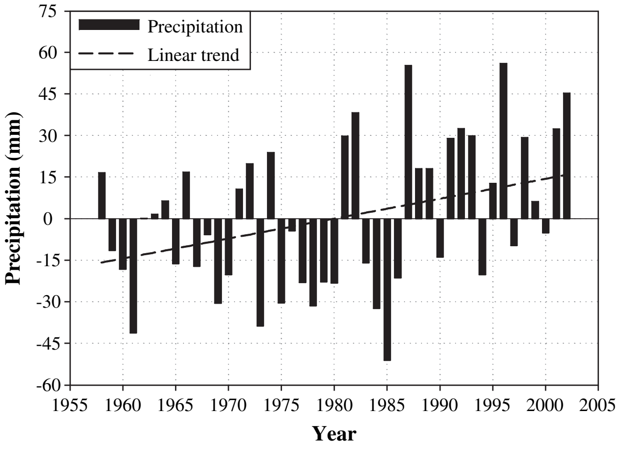

Fig. 3. Anomaly of average annual precipitation in the Tarim River Basin and its linear trend.

temperature decrease in spring, summer, autumn and winter were all high, especially in winter and spring (Fig. 4b). The annual temperature in the 1980s increased to some extent, all the seasonal temperature anomalies in the 1990s became positive, especially the autumn, making the 1990s the warmest decade in the subarea with the annual temperature 0.92 °C higher than the multi-annual average. Annual precipitation decreased during the period from the 1960s to the 1970s. But it increased to the multi-annual average in the 1980s and increased by 18.9% in the 1990s. The seasonal precipitation increase was also the highest in the 1990s. Temperature increase in autumn was the most significant, and the local warming–wetting trend was significant.

3.3.3. The Yarkand River subarea

In the Yarkand River subarea, the annual temperature was generally in a slight increase trend. In the 1990s it was only 0.24 °C higher than the multi-annual average, suggesting that the temperature increase trend in the subarea was not significant. The contribution of temperature increase in autumn and winter was higher (Fig. 4c). Annual precipitation in the 1970s was the lowest, but began to increase from the 1980s and increased by 20.7% in the 1990s. The precipitation significantly increased in spring and summer but decreased to some extent in autumn and winter. Viewing the whole subarea, temperature increase occurred mainly in autumn and winter, while precipitation increase occurred mainly in spring and summer.

3.3.4. The Hotan River subarea

In the Hotan River subarea, the change of temperature was not significant. The annual temperature was relatively high in the 1970s, but relatively low in the 1960s and 1980s, and was maintained at the multi-annual average in the 1990s. The change in temperature was generally low, generally not exceeding 0.50 °C. The temperature fluctuation was relatively high in autumn and winter but low in spring and summer (Fig. 4d). The change in precipitation was not so high and about 10% with some increase in summer and autumn, decrease in spring, and no significant change in winter. The annual change in both temperature and precipitation were low in the whole subarea.

Table 4
Information about the typical stations in 4 subareas of the headstream area of the Tarim River Basin.

Code name	Subarea	Typical stations
A	Kaidu-Kongque River subarea	Bayanbuluk, Dashankou, Yanqi
B	Aksu River subarea	Sharikilank, Xehera, Aksu
C	Yarkand River subarea	Kaqung, Kuruk, Taxkorgan
D	Hotan River subarea	Uruwat, Tongguzlok, Hotan

Both similarities and dissimilarities of the change characteristics of temperature and precipitation in the climatic subareas of headstream area of the Tarim River are found. The 1990s had the highest annual temperature and precipitation. The results are consistent with other findings (Shi et al., 2002; Yang and He, 2003). Although the climate in the drainage basin changed toward a warming–wetting trend, but the scale varied from subarea to subarea. The temperature increase was higher in the subareas of Aksu River and Kaidu-Kongque River located in the southern slope of the Tianshan Mountains than that in the subareas of Yarkand River and Hotan River located in the Kunlun Mountains. Annual precipitation increased by over 10% in all the subareas except that in the Hotan River subarea, and the precipitation increase was significant.

Although the annual temperature significantly increased in all the subareas in the 1990s, the scale of increase varied among seasons and subareas. The increase occurred mainly in autumn and winter in the subareas of the Kaidu-Kongque River, Yarkand River and Hotan River, but mainly in autumn and spring in the Aksu River subarea. Precipitation also increased differentially within seasons and subareas. The increase occurred mainly in summer in the subareas of the Kaidu-Kongque River and Yarkand River, but mainly in autumn in the subareas of the Aksu River and the Hotan River.

3.4. Effect on runoff by precipitation and temperature

River flows are a synthesis of what happens to precipitation, evapotranspiration and other components of the hydrological cycle. As Tarim river basin is located in an arid region, some of the small rivers are characterized with perennial streams in response to the precipitation pattern in the study area. The detection of the long-term trend on streamflow may be problematic due to the large number of zero values. We have to use average annual runoffs in this study. The annual runoff time series in several tributaries and along the mainstream of the Tarim River over 1950–2003 are used. The standardized streamflow runoffs from four major tributaries: Aksu, Yarkand, Hotan and Kaidu-Kongque rivers during the past 50 years were shown in Fig. 5.

It was observed that the streamflow in Aksu River, Yarkand River and Kaidu-Kongque River showed an increase tendency, but there was a subtle reduction on the Hotan River. Table 5 presented the result of the Mann–Kendall test. It was interesting to note that only the Aksu River showed an obvious tendency of increase by coefficient 0.41 and with 95% level of confidence. Both Yarkand River and Hotan River did not show a clear trend. The streamflow on Kaidu-Kongque River showed an indistinctive trend. However, the total volume of water from the headstreams was actually increasing during the past 50 years. That might be due to the effect by local climate change.

The correlations between runoff and climatic variables, temperature and precipitation (Table 6), in the four tributaries showed that there did be a relationship between them. For the Aksu River, the main tributary, a strong correlation existed at 1% significance ($p = 0.000$). It is the same with the Kaidu-Kongque River. For the Hotan River, temperature dominated the change of runoff supplemented by glaciers. However, for the Yarkand River there was no correlation between these three variables, which was mainly because that the river is recharged by glaciers, while the temperature of this subarea increased in winter and autumn significantly. The discordance in time between them resulted in an indistinctive runoff. Anyway, runoff was affected by climate change as a whole. Take the Aksu River and Kaidu-Kongque River for instance to establish the relations between hydrological variations and local climate change as follows.

$$\text{Aksu River}: \quad R = -4.968 + 0.226T + 0.287P \quad \left(R^2 = 0.680\right)$$

$$\text{Kaidu-Kongqi River}: \quad R = -15.842 - 9.038T + 0.311P \quad \left(R^2 = 0.603\right)$$

3.5. Association between temperature/precipitation and ENSO

Mechoso and Iribarren (1992) have found a relationship between the ENSO phase and streamflow in the Negro and Uruguay rivers. Generally, negative streamflow anomalies are associated with the cold phase, and positive anomalies with the warm phase

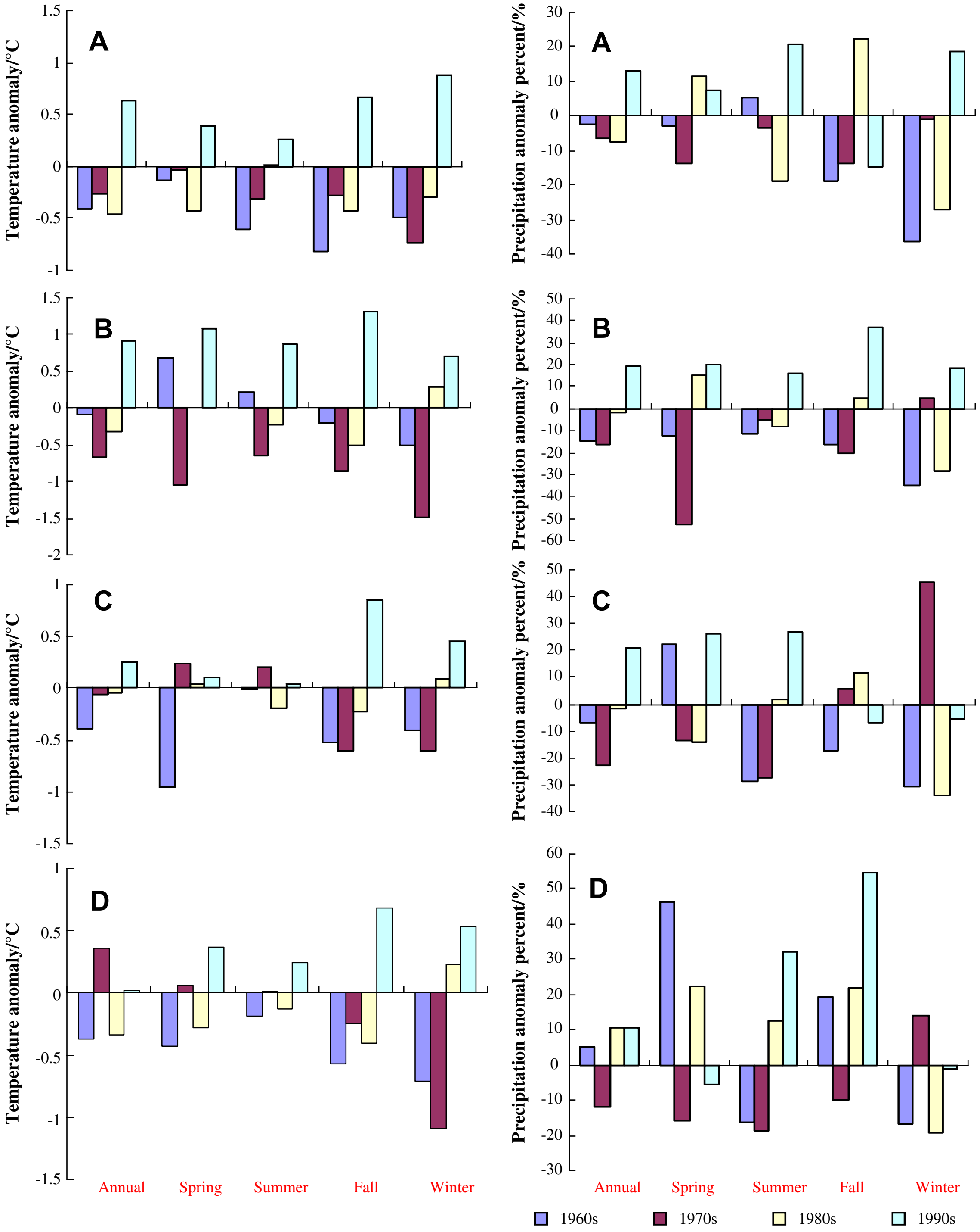

Fig. 4. Inter-annual change of temperature and precipitation of different head streams in the Tarim River Basin. The letters A, B, C, D represent the area of Kaikong River, Aksu River, Yarkand River and Hotan River, respectively.

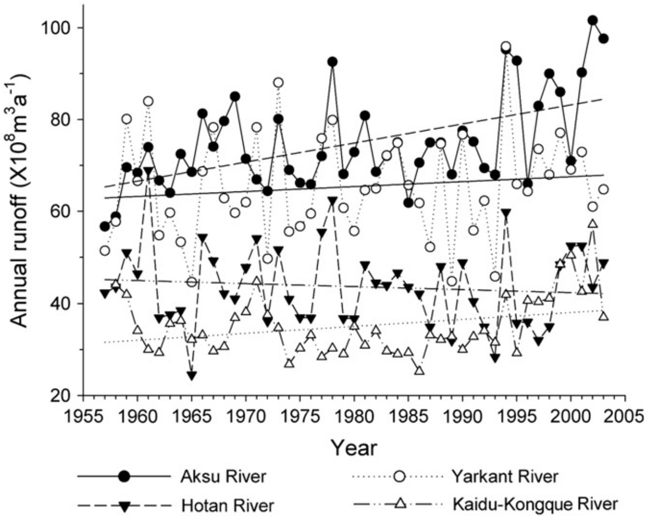

Fig. 5. Streamflow runoff of the four major tributaries of the Tarim River during the period 1957–2003.

in the Equatorial Pacific. Similar teleconnection also was found by Bordi and Sutera (2001). The effects of climate change, ENSO and other events on the change of temperature and precipitation as well as the serious climatic anomaly caused by ENSO events have been closely monitored and studied all over the world. In this paper, the relation between the El Nino event and the hydrological process in the study area was examined. We found that 7 positive and 4 negative anomalies of annual temperature and 4 positive and 7 negative anomalies of annual precipitation occurred in the years when the El Nino developed (Fig. 6), suggesting that the temperature increase and the precipitation decrease were dominant in the years when the El Nino event occurred. We also found that 5 positive and 6 negative anomalies of both annual temperature and annual precipitation occurred in the years when the La Nina event developed, suggesting that the effect of the ENSO on the annual temperature and annual precipitation was very low in the years when the La Nina event developed. The research results also showed that 6 positive and 5 negative anomalies of both annual temperature and annual precipitation occurred in next years after the El Nino event developed, and the difference between these two was not significant, suggesting that there was no significant effect of the ENSO.

Although there were some possible relations between the annual temperature and annual precipitation and the ENSO, the independence test results reveal that the correlations in the years as well as the following years after ENSO were very low: $x^2_{NT} = 1.331$, $x^2_{NP} = 0.612$, $x^2_{N'T} = 0.402$, $x^2_{N'P} = 0.402$, $x^2_{LT} = 0.064$, $x^2_{LP} = 0.005$, where, N is the year when the El Nino event develops, N' is the next year after the El Nino event develops, L is the year when the La Nina event develops, T is the temperature, and P is the precipitation. Such results may indicate that the relations between the annual temperature and precipitation in the drainage basin and the ENSO events were not correlated.

Table 5
Monotonic shift test for four streamflow time series on tributaries.

River	Mann–Kendall test		
	Z_0	β	H_0
Aksu River	3.327	0.3700	R
Yarkand River	0.649	0.1113	A
Hotan River	−1.301	−0.1123	A
Kaidu-Kongque River	1.10	0.11	A

Note: R – rejected, A – accepted., Significant level $\alpha = 0.05$.

Table 6
Correlations between runoff and climatic variables, temperature and precipitation.

	Aksu River		Yarkant River		Hotan River		Kaidu-Kongqi River	
	T	P	T	P	T	P	T	P
R	0.798**	0.761**	–	–	0.357*	–	0.347*	0.635**

Note: **Significant level $\alpha = 0.01$, *Significant level $\alpha = 0.05$.

Further independence test of the seasonal temperature and precipitation with the El Nino and La Nina events revealed that the temperature in autumn and the precipitation in summer were correlated with the El Nino event in the years when the El Nino event develops, and their confidences were as high as 0.1 and 0.05 respectively (Table 7). The temperature in spring is related to the El Nino event in next years after the El Nino event occurs only. The temperature in summer and autumn is related to the La Nina event in the years when the La Nina event occurs. Such results suggest that the anomaly of precipitation in the drainage basin in summer was more significant in the years when the El Nino event develops than that in following year after the El Nino event occurs and in the years when the La Nina event occurs. Contrastly, the anomaly of temperature in following year after the El Nino event occurs and in the years when the La Nina event occurs was more significant than that in the years when the El Nino event occurs. Temperature change in autumn and precipitation change in summer in the drainage basin are extremely significant and dominated by positive anomalies in the years when the El Nino event developed. It is obvious that the temperature in autumn and precipitation in summer were high in the years when the El Nino event occurs. Although flood disasters might occur easily, they become less serious as the temperature and rainfall did not increase coinstantaneously. Moreover, the high temperature in autumn can maintain the glacier melt and recharge the rivers for a long time. This is beneficial for users of water resources in the drainage basin. But we still need to pay great attention to flood disasters.

In following year after the El Nino, a significant anomaly of temperature in spring occurs. It is dominated by negative anomaly.

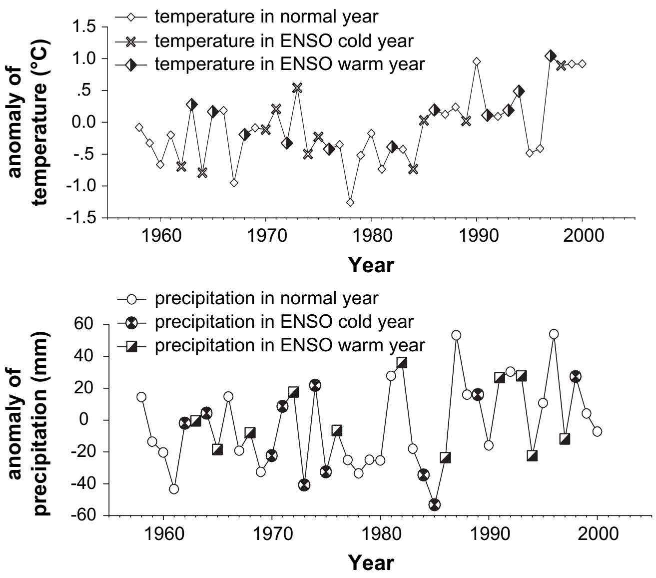

Fig. 6. Anomaly of mean annual temperature and annual precipitation in the Tarim River Basin and the year with the ENSO events.

Table 7

χ^2 test between temperature and precipitation of four seasons and El Nino, La Nina in the Tarim River Basin.

	Temperature				Precipitation			
	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter
El Nino years	0.940	0.917	2.790	0.072	1.331	5.074	0.368	0.018
The next year of El Nino	3.361	0.243	0.186	0.940	0.156	1.747	0.012	0.799
La Nina years	1.283	2.760	3.361	0.940	0.917	1.747	1.747	0.018

But the temperature change in other three seasons and precipitation change in all seasons were not significant. These phenomena suggest that effect of the El Nino on precipitation was slight, but the effect on temperature continuously existed in the following year of the El Nino event. Spring drought may thus be more likely, affecting spring ploughing to a certain extent.

During the La Nina event years, temperature in summer and autumn showed a significant anomaly and usually by negative anomaly. The change of precipitation was similar to that in the following year after the El Nino event, suggesting that the effect was not significant. Although several La Nina events occurred after the year of an El Nino event, the temperature change during these two kinds of events is different, suggesting that the effect of the La Nina on the anomaly of temperature in summer and autumn is significant in the Tarim River Basin.

In conclusion, the effects of the El Nino and La Nina events on the annual temperature and annual precipitation in the drainage basin seems not significant, but the impacts on seasonal temperature and precipitation existed to a certain extent. The temperature in autumn and the precipitation in summer in the drainage basin are high during El Nino years. The temperature change in the drainage basin accords with that in the eastern part of west China, where the temperature was high and the precipitation decreased. In contrast, the precipitation in the drainage increased. Such results are consistent with other findings (Li et al., 2003; Ye et al., 2006). During the La Nina years and the following years after the El Nino, the temperature in the drainage basin decreased. Such a trend accords with that in the eastern part of west China. In contrast, the precipitation change is not significant and different from the situation in the eastern part of west China.

The Tarim River Basin is located in the central area of Eurasia, covering the main part of south Xinjiang. Although the drainage basin is far away from the vapor sources, some recent findings (Zhang and Shi, 2002) reveal that some large-scale outer vapor-source factors, such as the Atlantic surface temperature and ENSO, affect flood, precipitation and temperature significantly in the drainage basins in Xinjiang. Our results indicate that there is a certain effect of the ENSO on the climate change in the Tarim River Basin, and the climatic response in the drainage basin to such effect is significantly different from that in the eastern part of west China.

4. Conclusions and discussion

In this study we used Mann–Kendall and Mann–Whitney nonparametric tests to examine the long-term trends of air temperature and precipitation in the Tarim River Basin. Our results revealed that an abrupt change of both temperature and precipitation in the drainage basin occurred in the mid-1980s, and both temperature and precipitation performed a significant increase trend since the 1980s. We also found that the 1990s was the warmest decade since recent 50 years. Such climate change was coinstantaneous with that not only in the whole area of Xinjiang, but in the western parts of China also. During the last five decades, the temperature has been increased by 0.3 °C in China (Ding, 2002) and by 0.2 °C/decade in west China (Wang and Dong, 2002). The global temperature has been increased by 0.2–0.3 ° (IPCC, 2001). Other findings and evidence also showed that global climate has been significantly changed by different regional scales in the past 50 years (Shi et al., 2002). The warming–wetting trend in the Tarim River Basin should be a local response to global climate change.

The temperature increase and precipitation increase in the Tarim River Basin were significant, but they did not occur in all seasons, suggesting that the temperature increase occurred mainly in winter and autumn, and the precipitation increase occurred mainly in summer. Temporally, the 1990s is the decade with the highest annual temperature and precipitation, and experiencing the most significant temperature and precipitation increase in the drainage basin. The temperature increase was significant in all the subareas in the 1990s but in different seasons.

By analyzing streamflow runoff of the four major tributaries of the Tarim River during the period 1957–2003, we found, except Hotan River, that the streamflow in Aksu River, Yarkand River and Kaidu-Kongque River showed an increase tendency. And the results of nonparametric tests showed that only the stream flow at Aksu River showed a significant increasing monotonic trend. The annual runoff volume in the Aksu River increased by 10.9% since 1990 comparing with the average temperature during the period from 1958 to 1989. Both Yarkand River and Hotan River did not show a clear trend. The streamflow on Kaidu-Kongque River showed an indistinctive trend.

According to the independence test of the temperature and precipitation in the drainage basin with the El Nino event, we found that the El Nino and La Nina events affected the temperature and precipitation in some seasons although their effects on the annual temperature and annual precipitation were not significant. During El Nino years, the temperature in autumn and the precipitation in summer in the drainage basin were high. The temperature change in the drainage basin accords with that in the eastern part of west China, but the precipitation change does not. During the following years after the El Nino and in La Nina years, the temperature in the drainage basin decreased. Such a pattern was consistent with that in the eastern part of west China. The precipitation change in the drainage basin was not significant and different from the situation in the eastern part of west China, where the precipitation increased.

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